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RAMJET ENGINE FUEL INJECTION STUDIES

John T. Hojnacki

Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base, Ohio

November 1972

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TECHNICAL REPORT AFAPL-TR-72-76

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AIR FORCE AERO PROPULSION LABORATORY
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The primary objective of a liquid fuel injection system is to provide the combustion chamber with the proper amount of fuel in a pattern that will result in efficient combustion over the flight path of the missile. The relative amounts of fuel and air at the flameholding region are important in determining the efficiency of combustion. This local fuel/air ratio can be estimated once the penetration and spreading characteristics of the fuel spray are known. Then the proper distance of the fuel injector from this flameholding region can be selected to obtain stoichiometric conditions there.

From the local fuel/air ratio relationship, a family of curves was plotted, which are functions of downstream distance and overall fuel/air ratio. With these curves, the injector was placed at the appropriate distance from the flameholding region to obtain stoichiometric conditions at that region. Subsequent tests using the AFAPL Ramjet Burner Thrust Stand Facility verified that efficient combustion was achieved.

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FOREWORD

The work reported in this document was conducted during the period 5 October 1970 to 15 September 1971 under Project 3012, Task 301212, by the Experimental Group of the Ramjet Technology Branch, Ramjet Engine Division, Air Force Aero Propulsion Laboratory. The project engineer is John T. Hojnacki.

This report was submitted by the author 1 May 1972.

This report has been reviewed and is approved.

Edward T. Curran

EDWARD T. CURRAN, Chief
Ramjet Technology Branch
Ramjet Engine Division

ABSTRACT

The purpose of this investigation was to develop empirical methods for designing a fuel injection system applicable to sudden expansion burners using a coaxial inlet. An integral rocket/ramjet missile may utilize this type of fuel system.

The primary objective of a liquid fuel injection system is to provide the combustion chamber with the proper amount of fuel in a pattern that will result in efficient combustion over the flight path of the missile. The relative amounts of fuel and air at the flameholding region are important in determining the efficiency of combustion. This local fuel/air ratio can be estimated once the penetration and spreading characteristics of the fuel spray are known. Then the proper distance of the fuel injector from this flameholding region can be selected to obtain stoichiometric conditions there.

From the local fuel/air ratio relationship, a family of curves was plotted, which are functions of downstream distance and overall fuel/air ratio. With these curves, the injector was placed at the appropriate distance from the flameholding region to obtain stoichiometric conditions at that region. Subsequent tests using the AFAPL Ramjet Burner Thrust Stand Facility verified that efficient combustion was achieved.

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SYMBOLS

a, b, c, d	exponents
X	penetration distance, distance cross-stream parallel to injector axis (inch)
Y	spreading distance, width of fuel spray (inch)
Z	downstream distance parallel to air stream axis (inch)
ρ_j	density of liquid (lb/ft^3)
ρ_a	density of air stream (lb/ft^3)
V_j	liquid velocity (ft/sec)
V_a	air stream velocity (ft/sec)
do	orifice diameter (inch)
σ	liquid surface tension (dyne/cm)
μ_j	viscosity of liquid (lb_m/ft-sec)
$(f/a)_1$	local fuel/air ratio
$(f/a)_\infty$	overall fuel/air ratio
A_a	area of inlet (in^2)
A_f	area of fuel (in^2)
$\dot{m}_f$	mass flow fuel (lb_m/sec)
$\dot{m}_a$	mass flow air (lb_m/sec)

SECTION I

INTRODUCTION

The first part of this investigation was conducted to determine the penetration and spreading correlation which would predict most accurately the penetration and spreading that occurs in the coaxial inlet of a sudden expansion ramjet engine combustor using a single plain-stem cross-stream injector. Then, from the proper correlation, we drew empirical design curves which would position the injectors at a distance from the flameholding region for maximum combustion efficiency.

Chelko (Reference 1) used a dimensional analysis involving all the variables that were expected to affect the penetration distance for cross-stream injectors. He used a single liquid (water) and a constant air stream velocity. His variables were orifice diameter and air stream density. He assumed that the discharge coefficient was equal to 1.00, which may not have been valid. He made no attempt to measure the spreading of the water spray. His result was:

$$\frac{X}{d_o} = .45\left[\left(\frac{V_j}{V_a}\right)^{.95}\left(\frac{\rho_j}{\rho_a}\right)^{.74}\left(\frac{Z}{d_o}\right)^{.22}\right] \tag{1}$$

Ingebo (Reference 2) used a variety of liquids to analyze data obtained in 1957 (Reference 3) and correlated maximum penetration distance to Reynolds and Weber numbers and injector diameters for cross-stream injectors. His results were:

$$\frac{X}{d_o} = 1.8\left[\left(\frac{\rho_j V_j^2}{\rho_a V_a^2}\right)^{.7}\left(\frac{\sigma}{\mu_j V_j}\right)^{.7}\right] \tag{2}$$

He predicted that penetration is influenced by the ratio of the surface tension to the liquid viscosity. (Chelko's correlation makes no such prediction.) Ingebo also did not measure spreading.

Lastly, Geery and Margetts (Reference 4) used cross-stream injection of water and the same analysis as Chelko to correlate their data. Their main variable was injector diameter, which was varied from 0.0625 to 1.5 in.

They also correlated spreading distance. Their results were:

For penetration:

$$\frac{X}{d_o} = 2.0 \left(\frac{\rho_j V_j^2}{\rho_a V_a^2} \right)^{.5} \left(\frac{Z}{d_o} \right)^{.27} \tag{3}$$

And for spreading:

$$\frac{Y}{d_o} = 2.6 \left(\frac{Z}{d_o} \right)^{.3} \tag{4}$$

As can be noted, the results obtained by each of the previous investigators were different.

SECTION II

TEST HARDWARF

The test hardware, shown in Figure 1, simulated the inlet of a sudden expansion ramjet engine combustor. The inlet is circular in shape with an inner diameter of 2.5 inches and a length of 12 inches. The injector was placed 1 inch from the end of the inlet. The test liquids were injected at right angles to the air stream from a single plain injector using pressurized nitrogen. There was no chamber at the end of the inlet, so the liquids were expelled intc the atmosphere. Liquid temperatures were monitored and did not vary significantly from 60°F.

The injector, Figure 2, was fabricated from a Gyrolock reducer fitting. The 1/16-inch portion was machined off, and a 10-32 bolt was soft-soldered in its place. A 0.0405-inch diameter hole was then drilled in the center of the bolt. Two injectors were used in the investigation, one 0.0405 and the other 0.023 inch in diameter.

Air was supplied from the main laboratory air supply and was metered with an orifice plate installed in the supply duct. The mass average velocity for the experiments was varied from 300 to 700 feet per second. The air temperature was not varied and stayed constant around 60°F.

A schlieren optical system, Figure 3, was used to define the lower edge of the injected spray. It consisted of two reflecting mirrors, a light source, two knife edges, and a camera. The light from this type of system was found to more clearly define the lower edge of the fuel spray.

The instrumentation consisted of an orifice plate for monitoring the air flow, a pressure gage for setting up stream air pressure, a thermocouple for monitoring air temperature, and a thermocouple for monitoring liquid temperature.

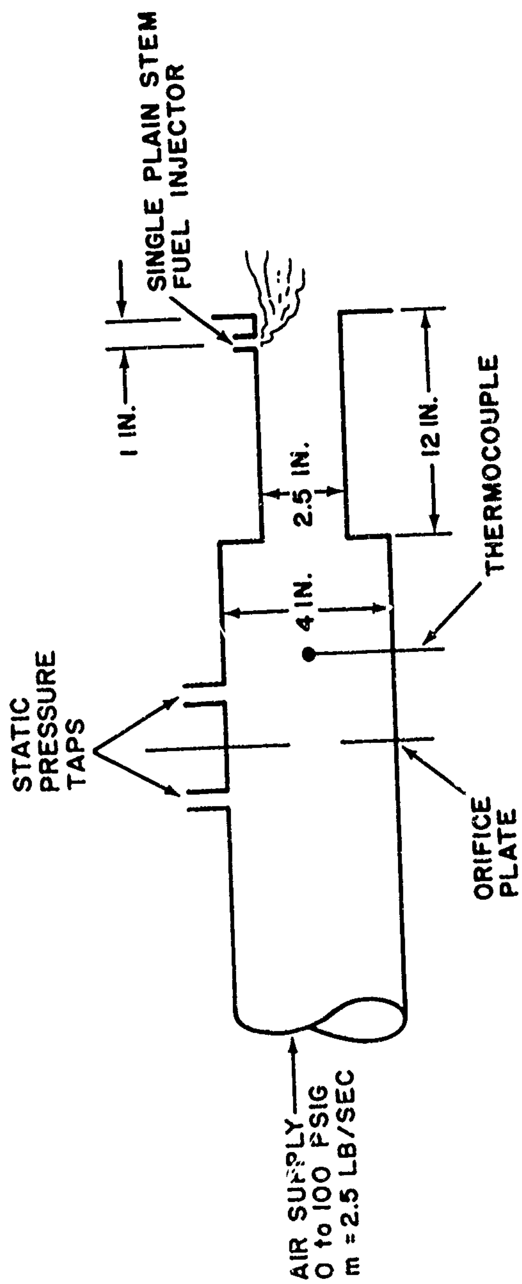


Figure 1. Schematic of Test Installation

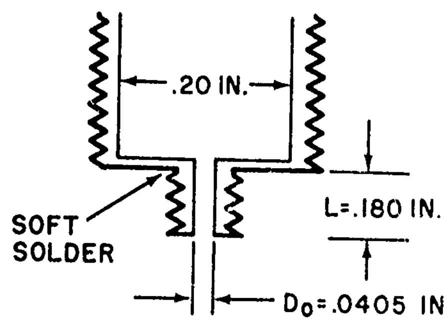
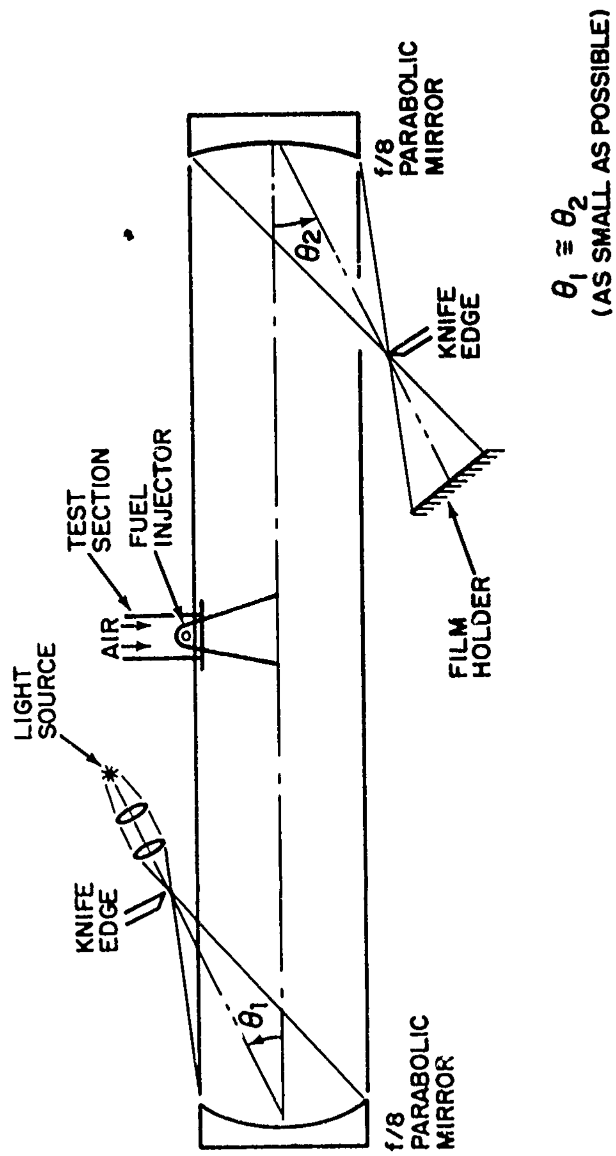


Figure 2. Sketch of Injector



Top View

Figure 3. Single Pass "Z" Schlieren System

SECTION III

TEST PROCEDURE

Initially, the test plan consisted of trying to verify Ingebo's (Reference 2) correlations of penetration distance with a single liquid, JP-4 fuel. The injector was positioned one inch upstream to more nearly duplicate his test setup. The procedure was to hold the fuel pressure constant and then vary the air velocity from 300 to 700 feet per second in four increments. The penetration distance of the liquid into the airstream was determined from schlieren photographs taken at the exit of the 2.5-inch section (Figure 3). There were two reference edges in each photograph: one marked the inside diameter of the test section and extended out parallel to the axis of the section about three inches, and the other was the end of the test section, shown in Figure 4. The injector was located one inch from the end of the test section so the penetration distance was measured as the distance from the top reference edge at the end of the test section.

The measured penetration distances thus defined did not correlate with those obtained using Ingebo's equation and the physical characteristics of the fuel/air stream. The measured penetrations were always greater than those predicted by Ingebo's correlation. A more comprehensive study to find a better correlation was then undertaken using five different liquids: JP-4, RJ-5, water, ethylene gylcol, and trichloroethylene. The investigation was conducted over the following range of conditions.

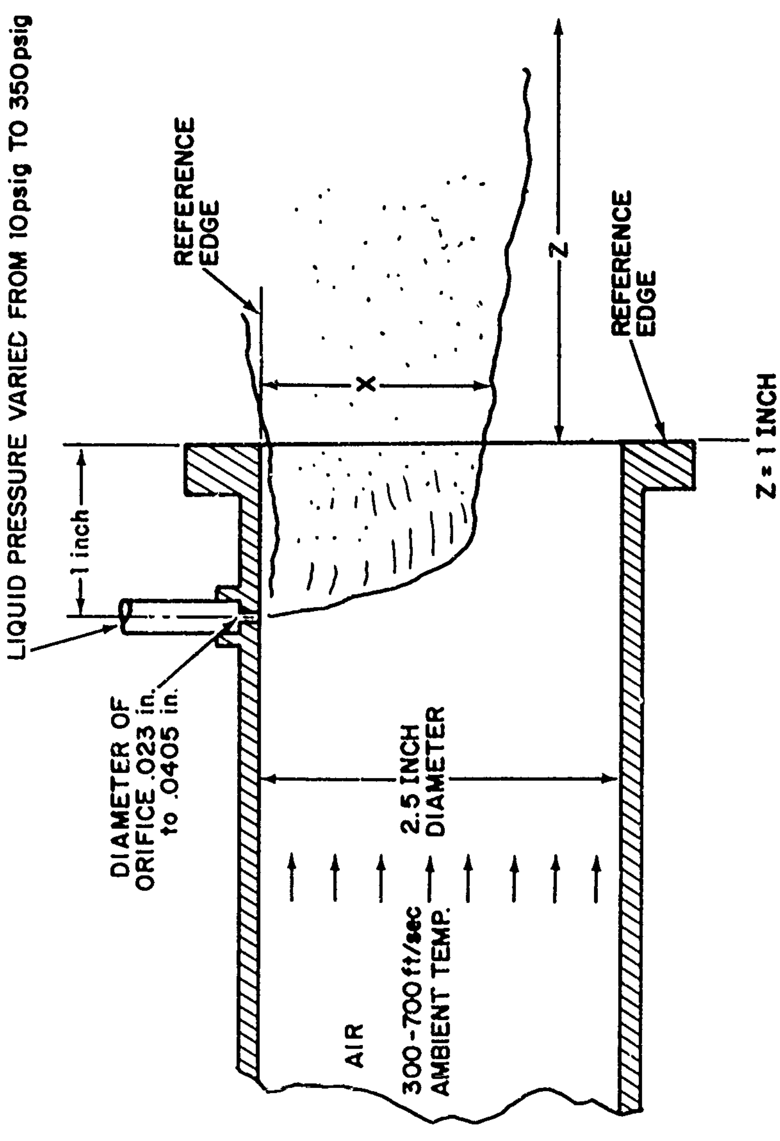
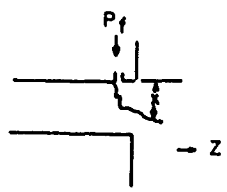


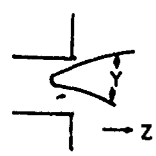
Figure 4. Penetration Experiment

Liquid	Injector Dia.	Viscosity μ_j (lb_m/ft-sec)	Density ρ_j (lb/ft^3)	Air Velocity V_a (ft/sec)	Liquid Velocity V_j (ft/sec)
	.0405				
JP-4	.0230	64.4×10^{-5}	47.6	300 to 700	40 to 260
RJ-5	.0405	27.7×10^{-3}	67.4	300 to 600	100 to 200
H_2O	.0405	67.4×10^{-5}	62.4	300 to 600	100 to 200
Ethylene Glycol	.0405	13.4×10^{-3}	69.2	300 to 600	100 to 200
Trichlor Ethelyene	.0405	37.2×10^{-5}	90.8	300 to 600	100 to 200

The density of the air, ρ_a was .0743 lb/ft^3 and the viscosity of the air, μ_a, was 1.2×10^{-5} lb_m/ft-sec. (For a listing of test conditions and penetration distances, see Table I in the Appendix).

In addition to determining penetration data, the width of the liquid spray as a function of downstream distance was determined by rotating the test section 90°. The dimensions X and Y in the sketch below define the dimensions of the fuel spray, where X is the penetration distance and Y is the width of the liquid spray.





SECTION IV

ANALYSIS

Chelko's method was used to analyze the data. The result of his analysis was an empirical expression of the form:

$$\frac{X}{d_o} = K\left[\left(\frac{V_j}{V_a}\right)^a \left(\frac{Z}{d_o}\right)^b \left(\frac{\mu_j}{\mu_a}\right)^c \left(\frac{\rho_j}{\rho_a}\right)^d\right] \tag{5}$$

where X and Z are the penetration and downstream distances, respectively, K is a constant, and a, b, c, d are exponents to be fitted empirically. V_j, μ_j, ρ_j are velocity, viscosity, and density of the jet, while V_a, μ_a, ρ_a are velocity, viscosity, and density of the airstream. Penetration was analyzed by varying one ratio at a time and plotting the penetration distance against the ratio on log paper to find the appropriate exponents.

1. V_j/V_a, VELOCITY RATIO

The air velocity was held at a fixed value and the fuel pressure was varied from 10 to 300 psi; results are given in Figure 5. The jet velocity was calculated from the calibration of flow rate and pressure drop across the injector. Calibration curves are given in Figures 6, 7, and 8. This procedure was repeated at four different air velocities. The exponent on this ratio was found to be close to 1.

2. Z/d_o, DOWNSTREAM DISTANCE/INJECTOR DIAMETER RATIO

Instead of only measuring the penetration of the fuel spray at the Z = 1 inch point, the penetration was measured as a function of downstream distance as the liquid and its pressure were varied. Results are given in Figure 9. The exponent on this ratio was found to be around 0.27.

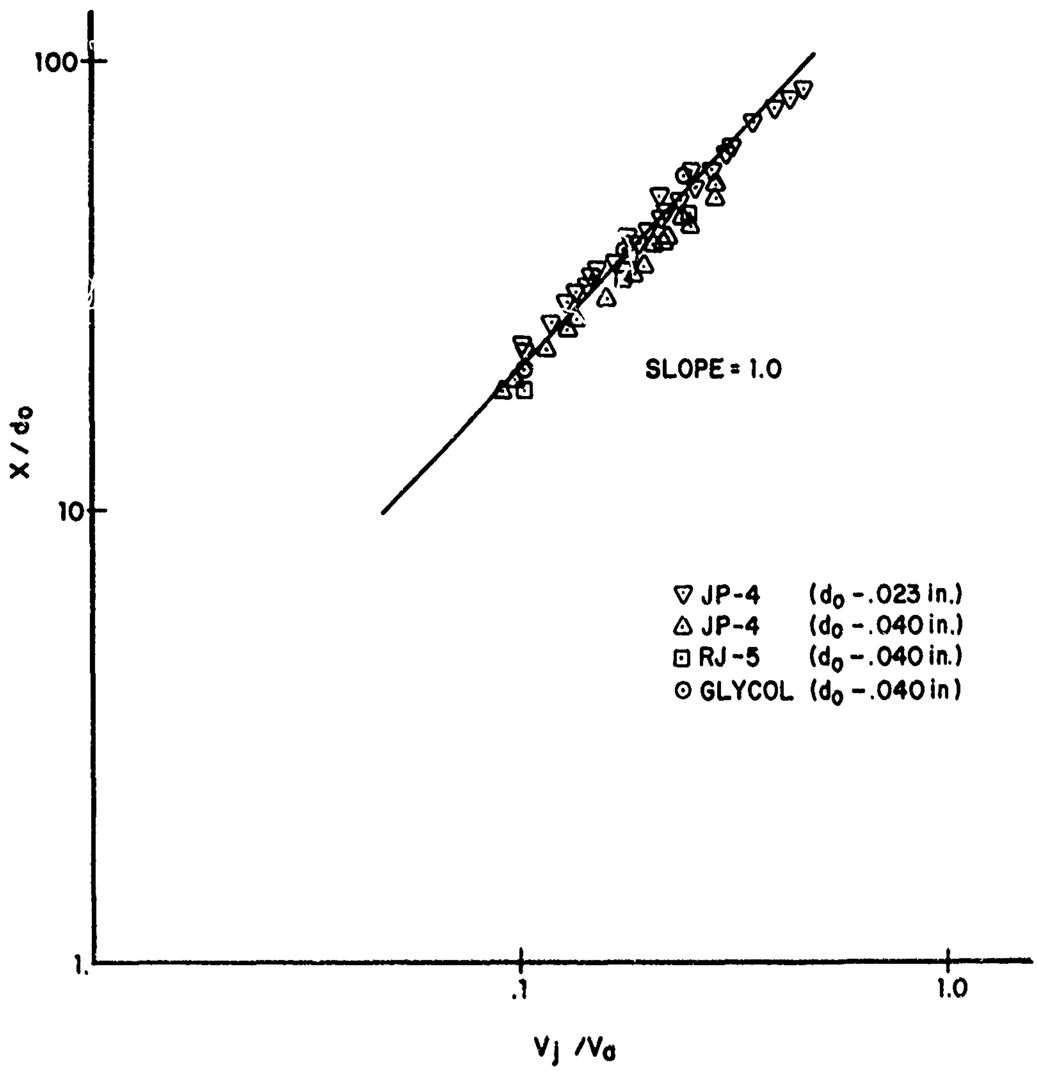


Figure 5. Changes in Penetration with Velocity Ratio

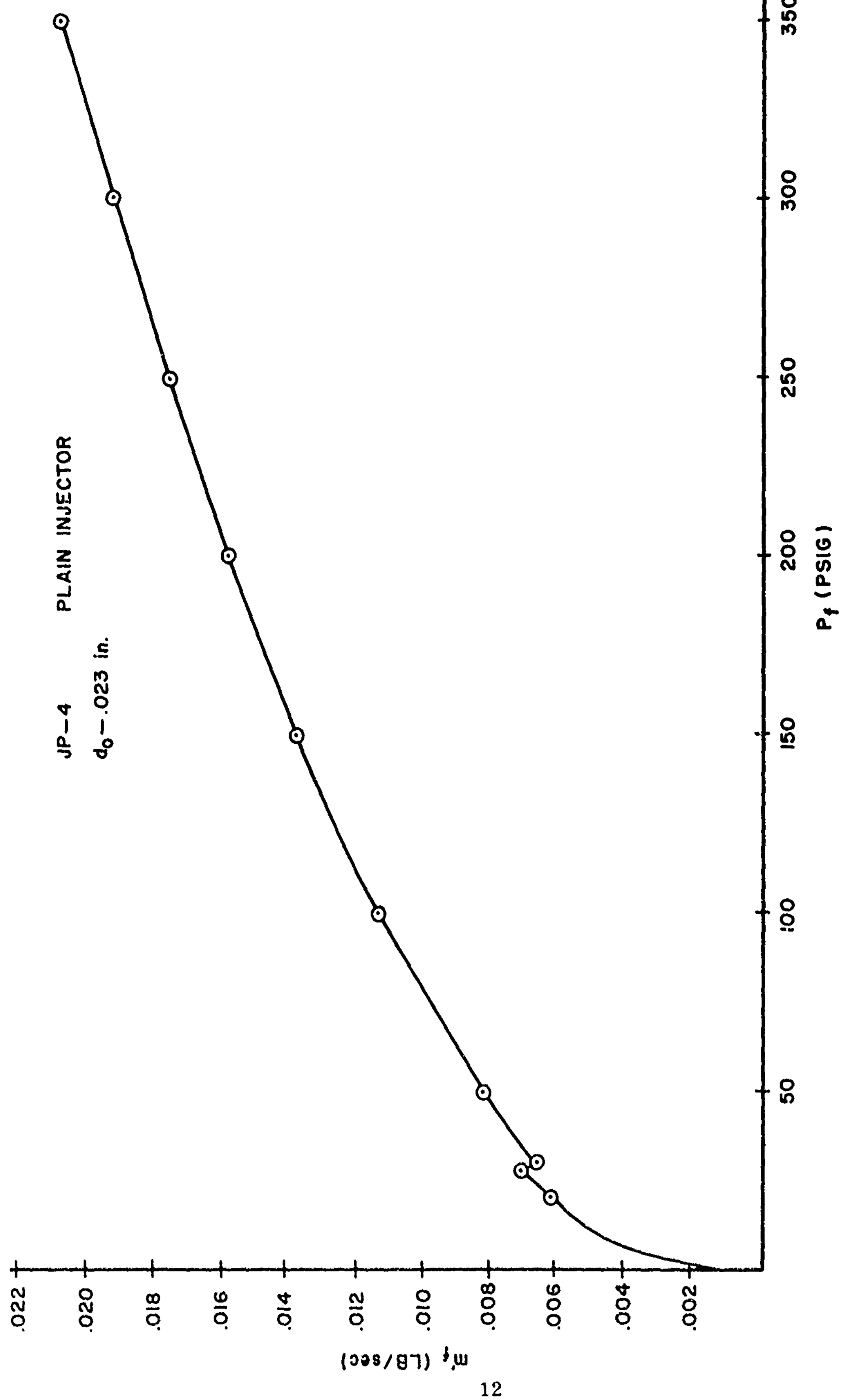


Figure 6. Mass Flow Calibration of Injector Fuel, JP-4

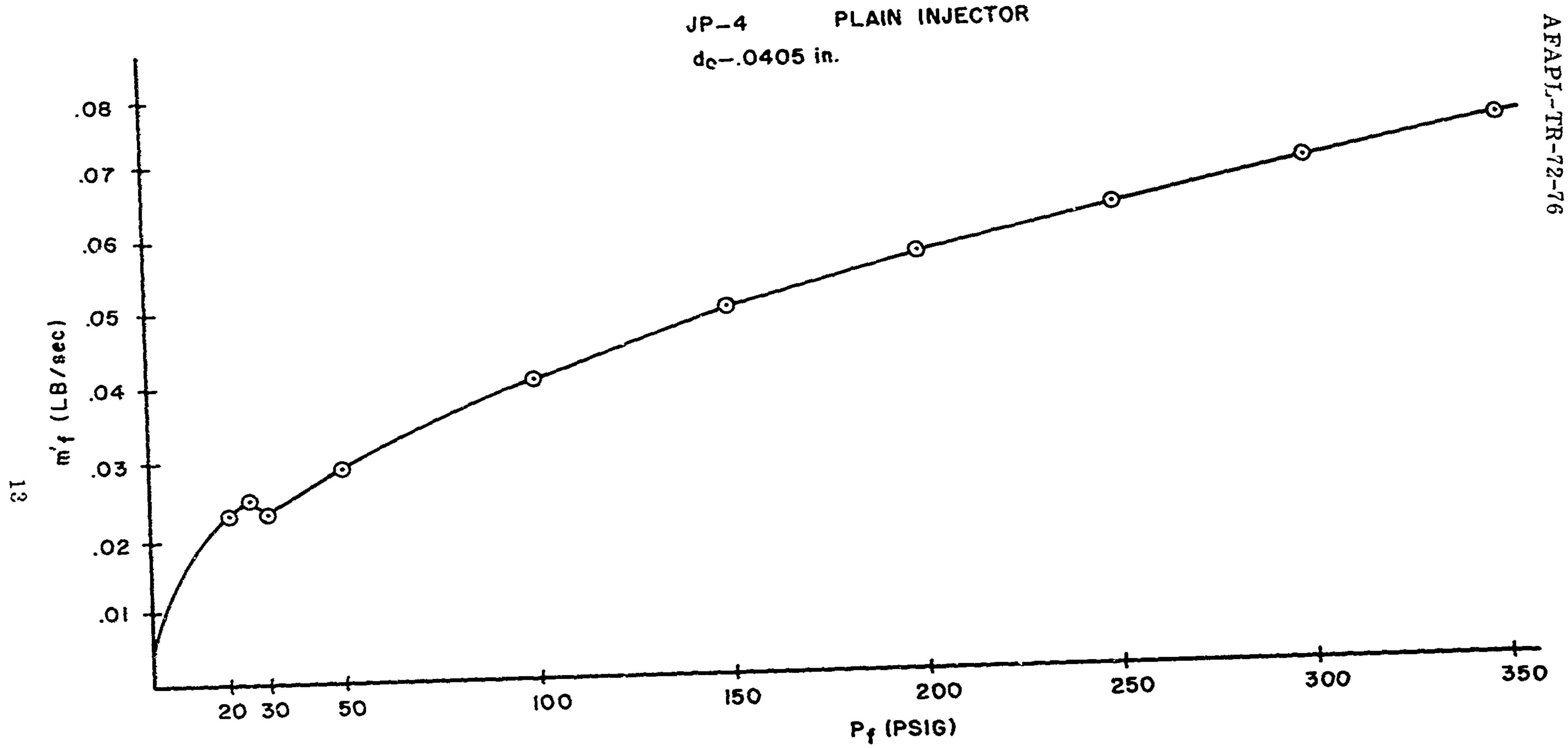


Figure 7. Mass Flow Calibration of Injector Fuel, JP-4

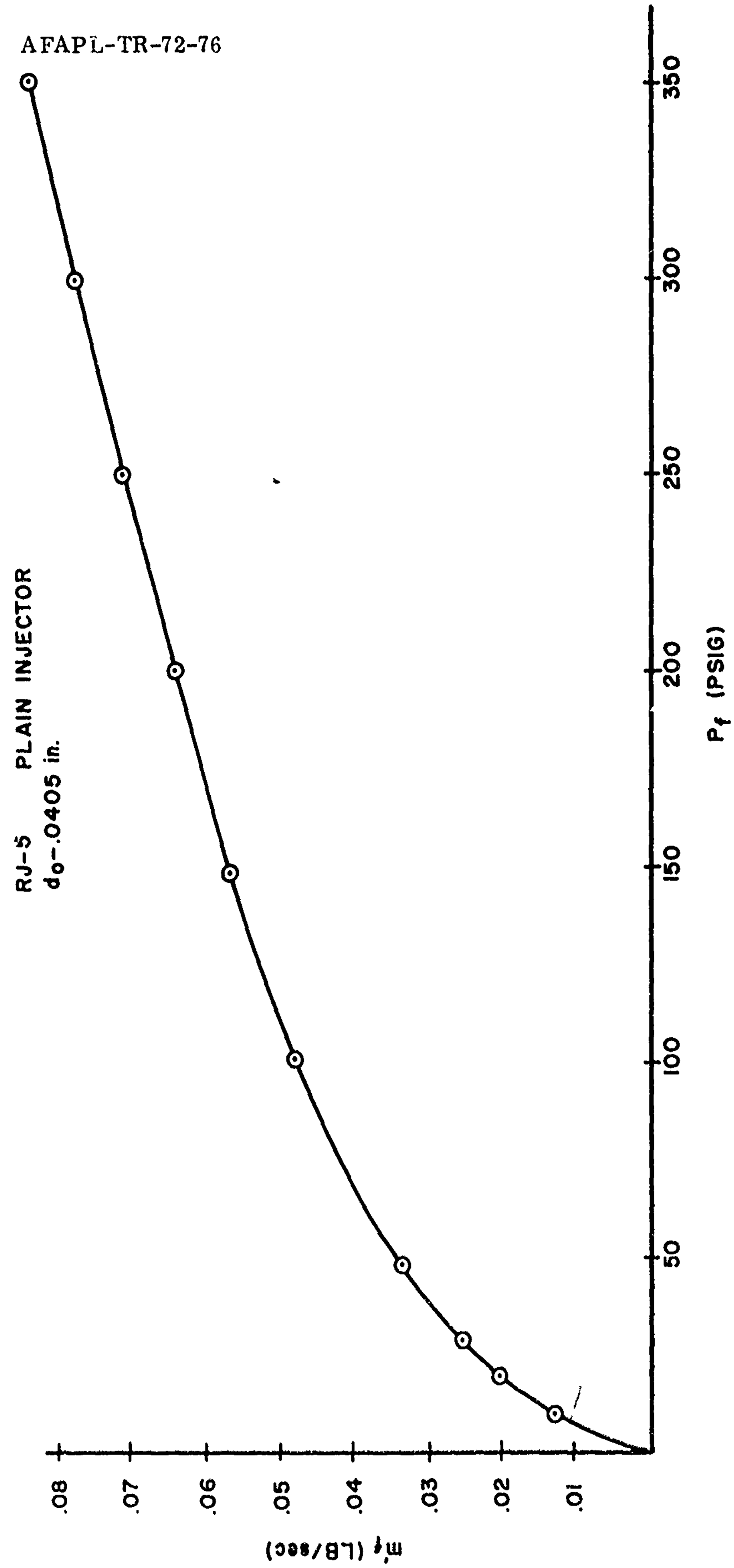


Figure 8. Mass Flow Calibration of Injector Fuel, Shelldyne RJ-5

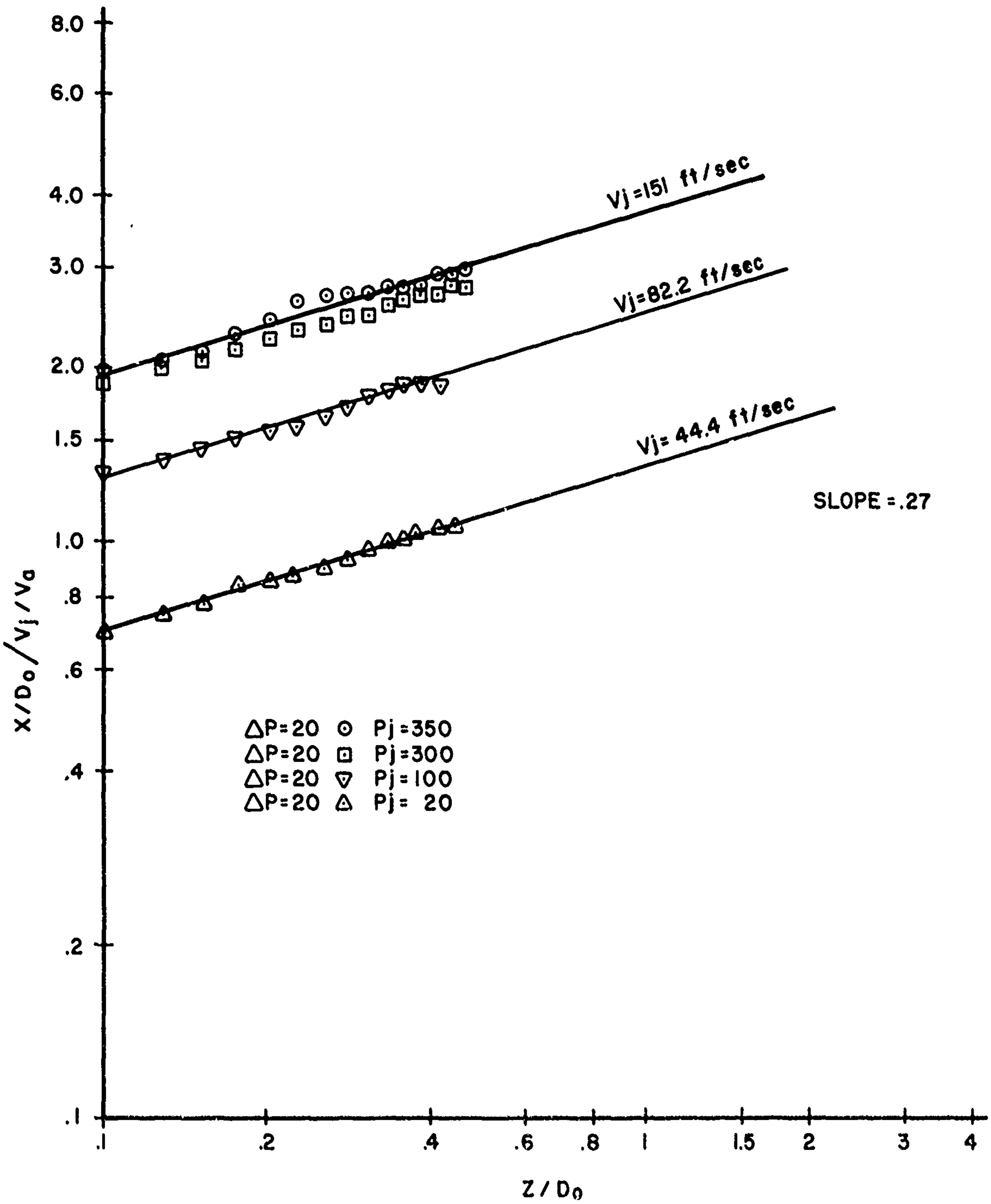


Figure 9. Changes in Penetration with Downstream Distance

3. ρ_j/ρ_{air}, DENSITY RATIO

Using liquids of varying density enabled the density ratio to be plotted as a function of penetration distance, velocity ratio, and downstream distance, as shown in Figure 10. The exponent on this ratio was found to be around 0.50.

4. μ_j/μ_{air}, VISCOSITY RATIO

The range of viscosity ratios used in this experiment varied from 31.0 for trichloroethylene and air to 2308 for RJ-5 and air. Results are given in Figure 11. When plotted against the other parameters the exponent becomes -0.096. The effect of viscosity on the penetration distance is so small that it was neglected in the final correlation. Chelko's experiment did not have a significant viscosity range to get a consistent effect of viscosity ratio on the penetration data. Neither did Geery and Margetts, as they used only water in their experiment. The effect of viscosity in Ingebo's correlation appeared as $(\sigma/\mu)^{.7}$, that is, surface tension divided by viscosity to the 0.7 power.

5. FINAL CORRELATION

The final correlation,shown in Figure 12, was obtained by plotting the penetration parameters X/d_o against the other parameters $(Z/d_o)^{.27}$ (V_j/V_a) $(\rho_j/\rho_a)^{.5}$. The constant was found to be 2.10. The final equation is:

$$\frac{X}{d_o} = 2.1\left(\frac{\rho_j V_j^2}{\rho_a V_a^2}\right)^{.5}\left(\frac{Z}{d_o}\right)^{.27} \qquad (6)$$

A plot of calculated penetration distance using previous investigators' equations versus measured penetration distance is shown in Figure 13.

The same procedure was followed for spreading. Although spreading was not tested under as many conditions as penetration was, it appeared to be insensitive to changes in test conditions, and varied with downstream distance only. Air velocity was held at 600 ft/sec and liquid velocity was varied from 76 ft/sec to 190 ft/sec. The temperature of the fuel was 65°F. These results

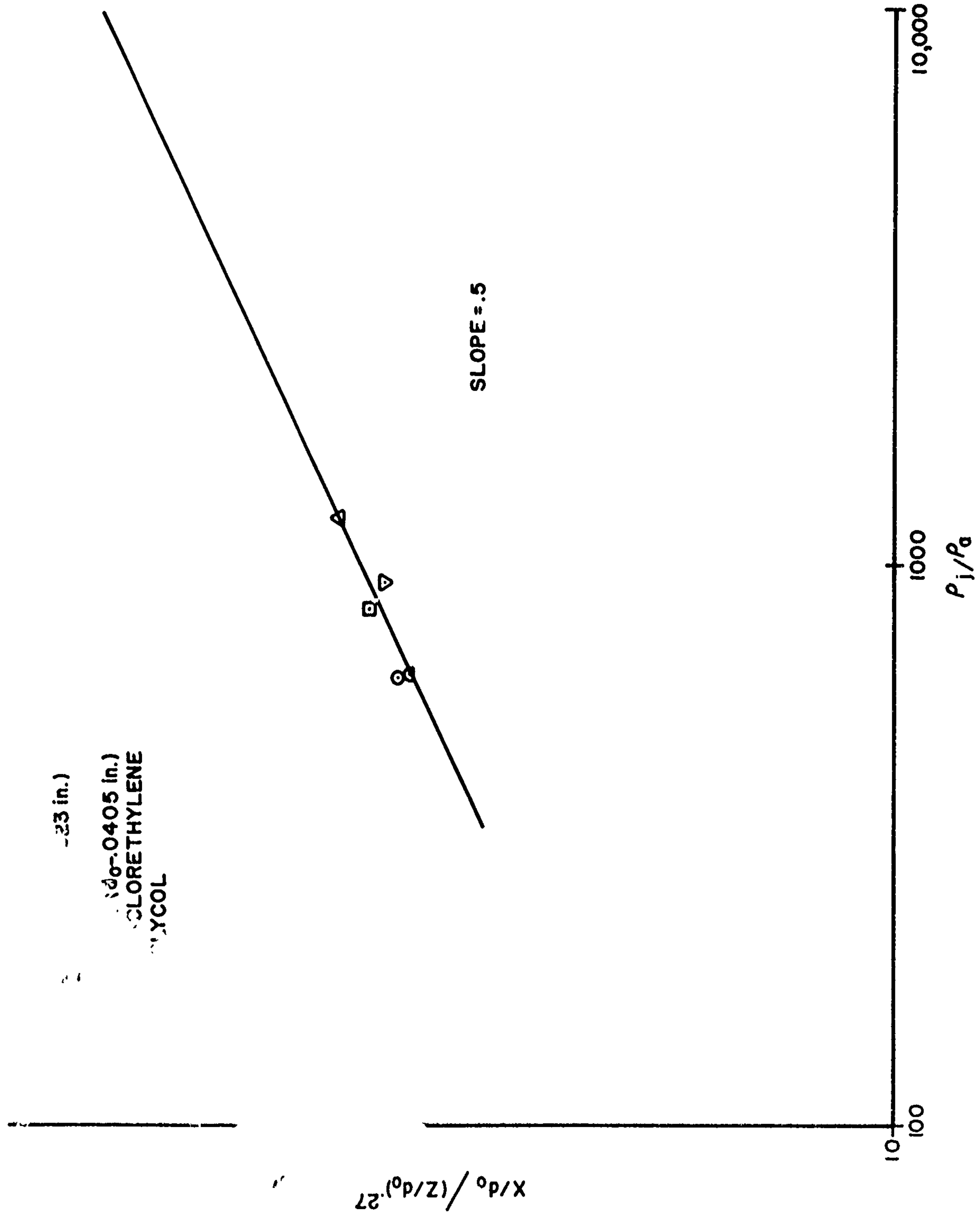


Figure 10. Changes in Penetration with Density Ratio

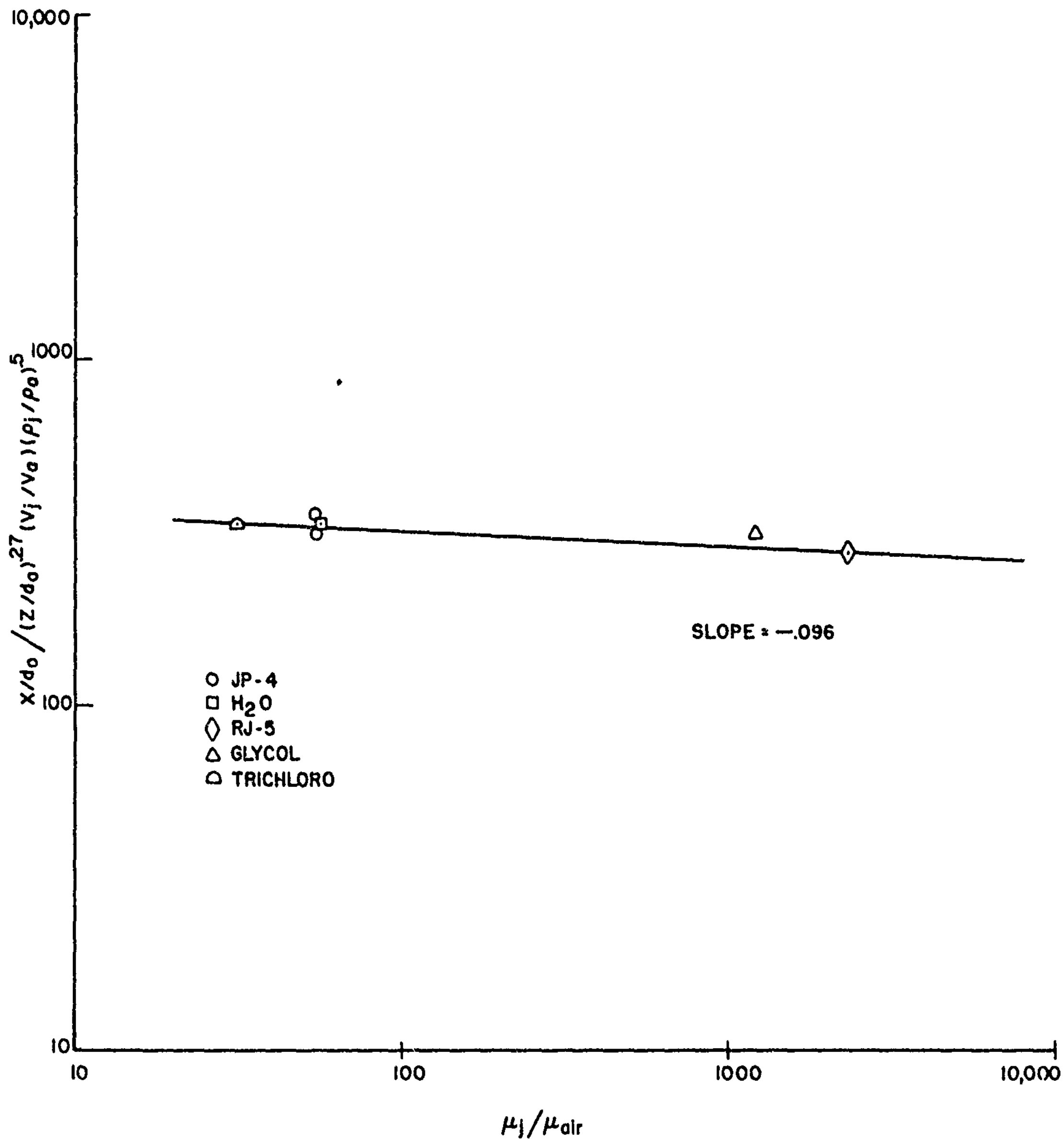


Figure 11. Changes in Penetration with Viscosity Ratio

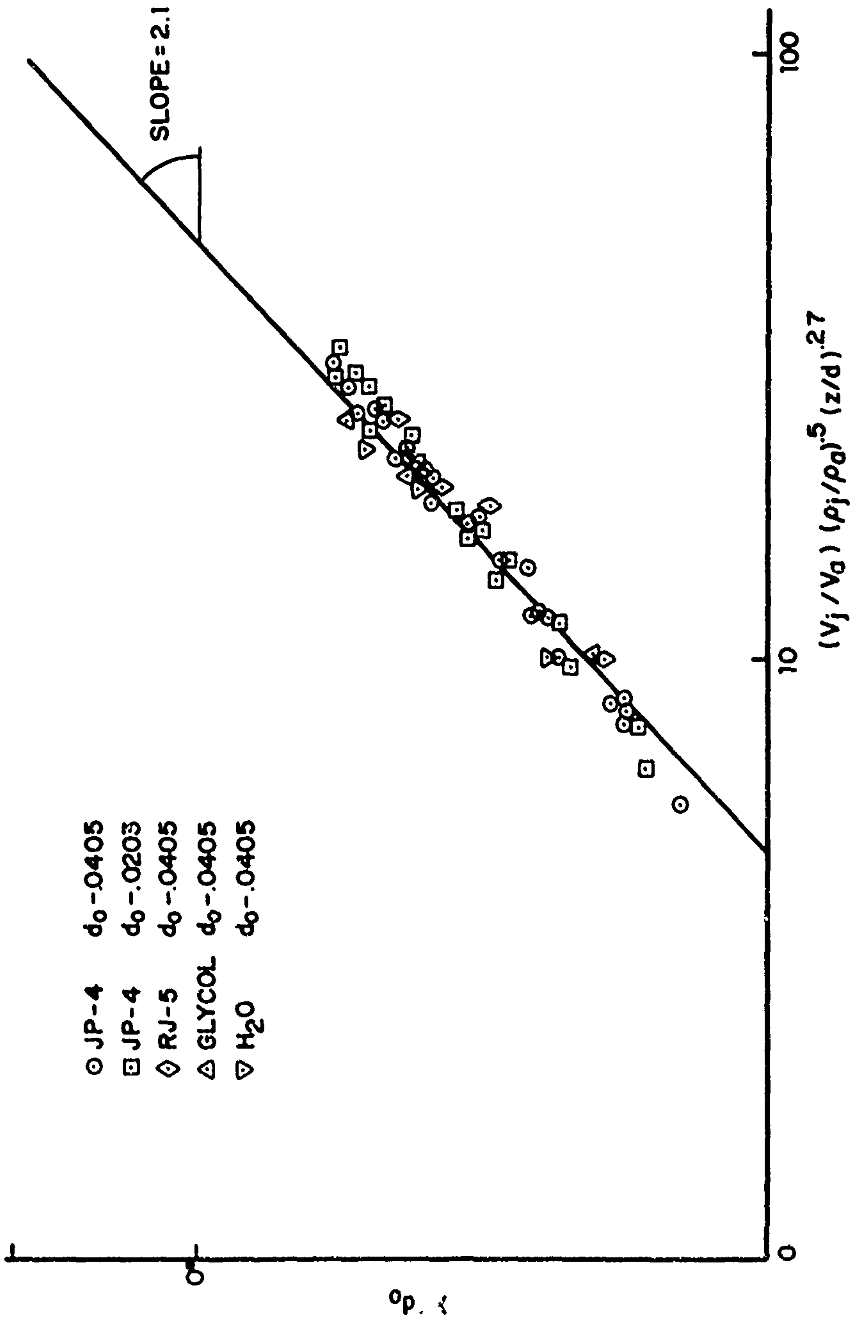


Figure 12. Penetration Correlation with Test Conditions

are identical to those obtained from diffusion from a line source in two dimensions; the final expression for this result, as shown in Figure 14, is

$$\frac{Y}{d_o} = 6.95\left(\frac{Z}{d_o}\right)^{.33} \tag{7}$$

The spreading and penetration equations can now be combined to give the following equation for local fuel/air ratio. (See Appendix for development of this expression.)

$$(f/a)_h = (f/a)_\infty \left(\frac{A_{inlet}}{14.6\, d_o^2}\right)\left(\frac{\rho_a V_a^2}{\rho_j V_j^2}\right)^{.5}\left(\frac{Z}{d_o}\right)^{-.6} \tag{8}$$

The results of this equation are plotted in Figure 15 for the engine geometry shown in Figure 16. From this figure a fuel injector location 2.5 inches from the flameholding region was chosen so that the local fuel/air ratio would be stoichiometric at that point for an overall fuel/air ratio of 0.01. The 0.01 fuel/air ratio was chosen because it was convenient for the test setup.

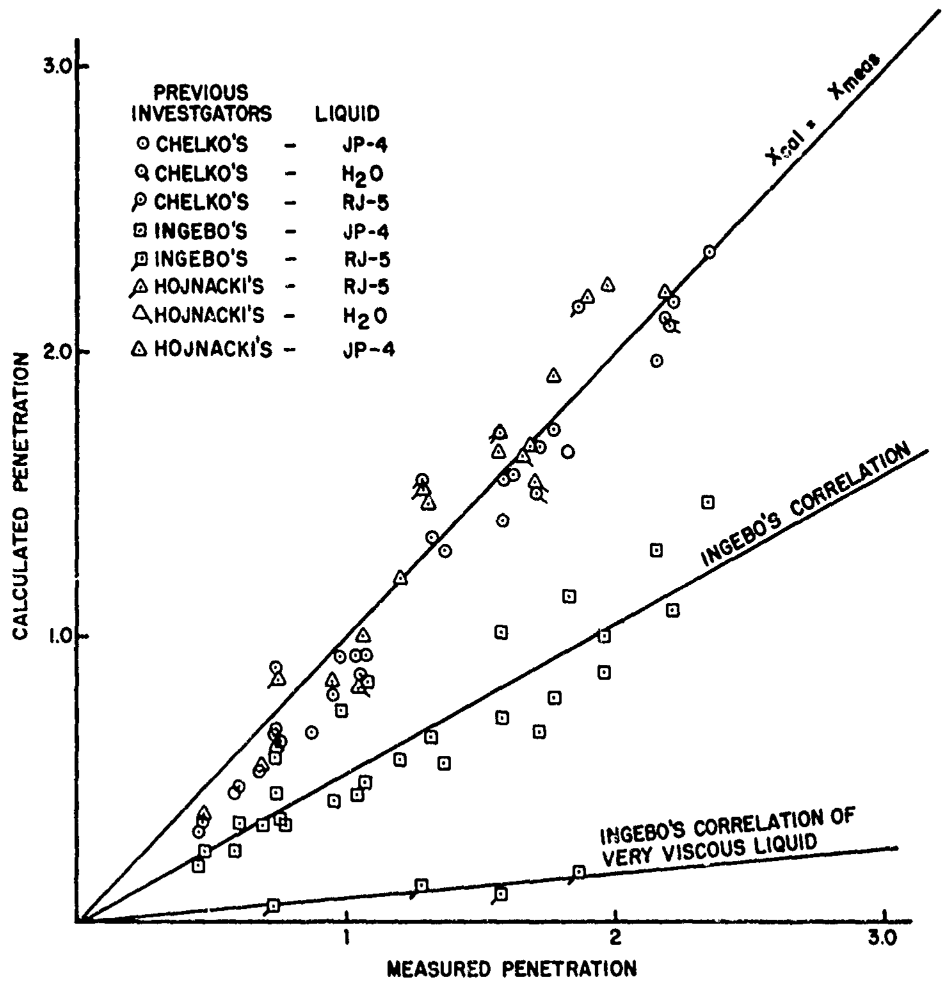


Figure 13. Calculated Penetration vs. Measured Penetration Using Previous Investigators' Equations

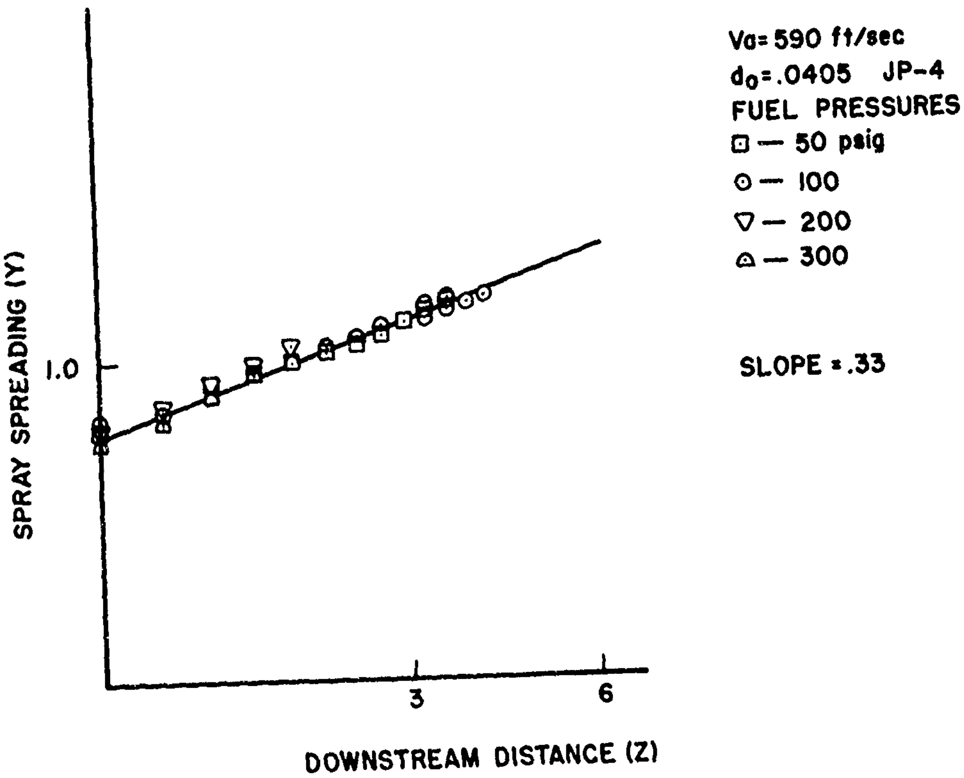


Figure 14. Spreading of Liquid Fuel Sprays in Subsonic Air Streams

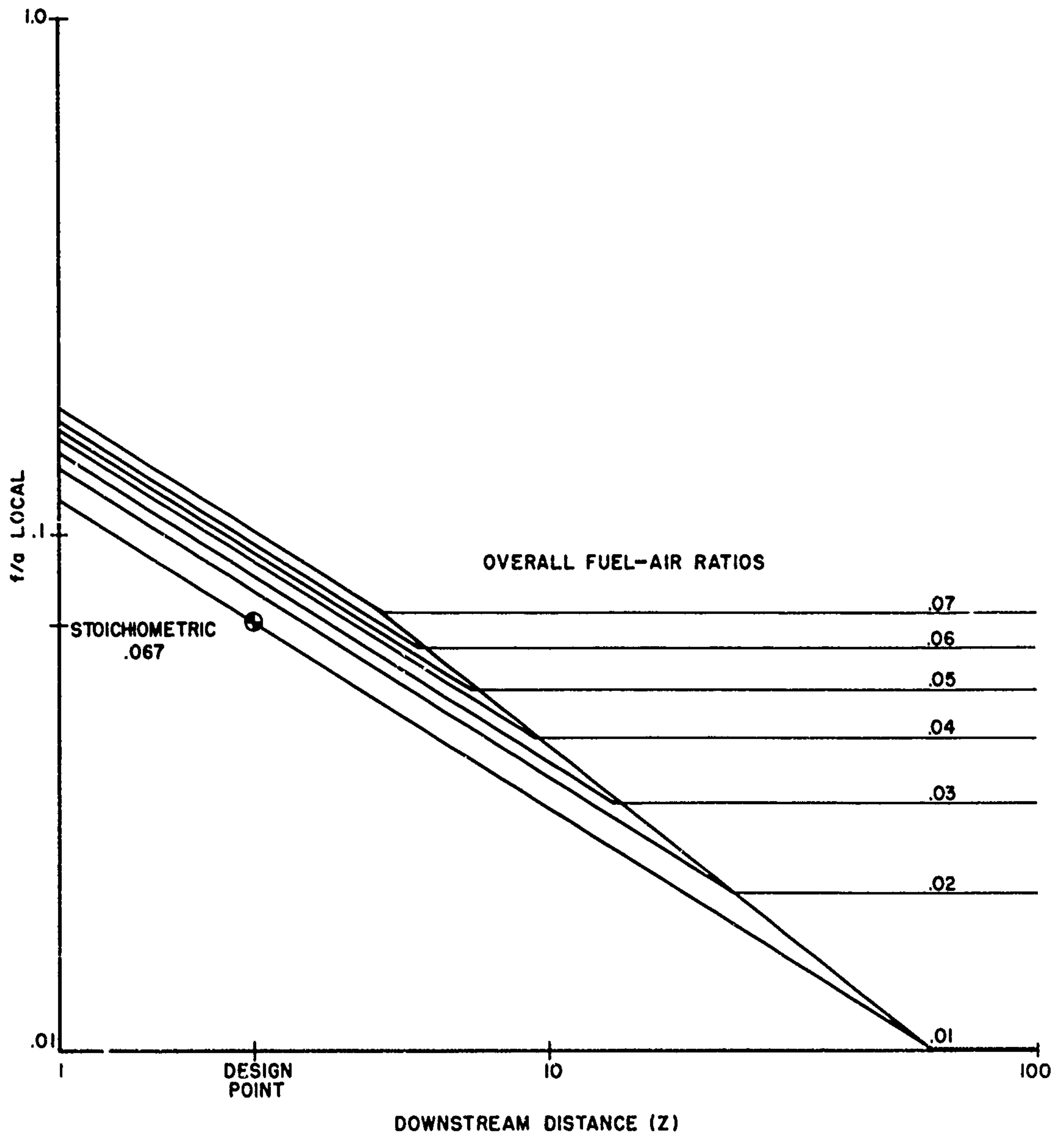


Figure 15. Variation of Local Fuel/Air Ratio for the Engine Design of Figure 1

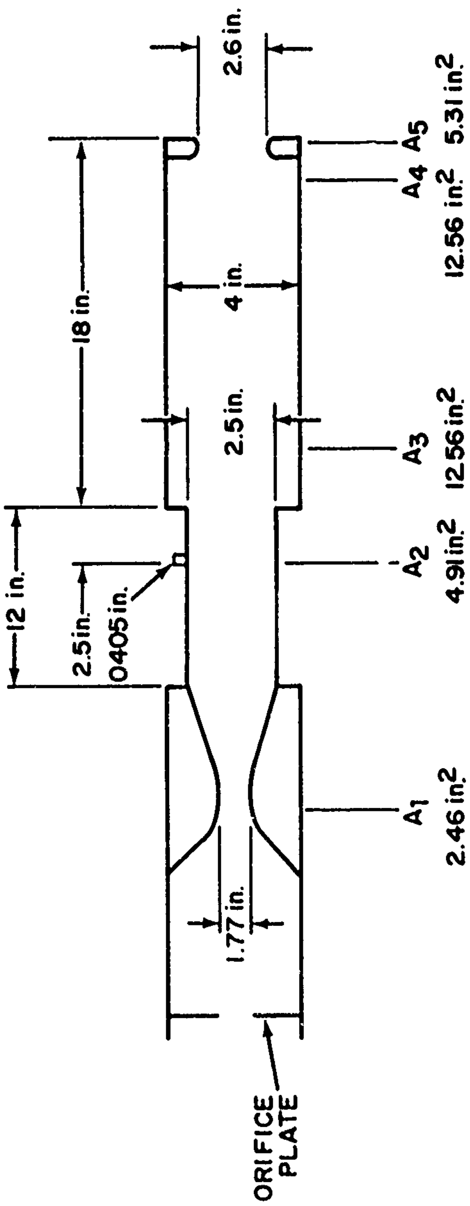


Figure 16. Baseline Engine

SECTION V

COMBUSTOR PERFORMANCE

The combustor testing was accomplished in hardware constructed as shown in Figure 16. Inlet air temperature, fuel type, and exit nozzle area were varied. The fuel was injected through one 0.040 in. diameter orifice. Ignition was accomplished by injecting hydrogen through a spark plug. The burner was radiation cooled only.

Combustor efficiency is shown in Figures 17 and 18 for the burner as a function of fuel/air ratio for JP-4 and RJ-5. The efficiency peaks in the vicinity of 0.01 fuel/air ratio, which is the design fuel/air ratio.

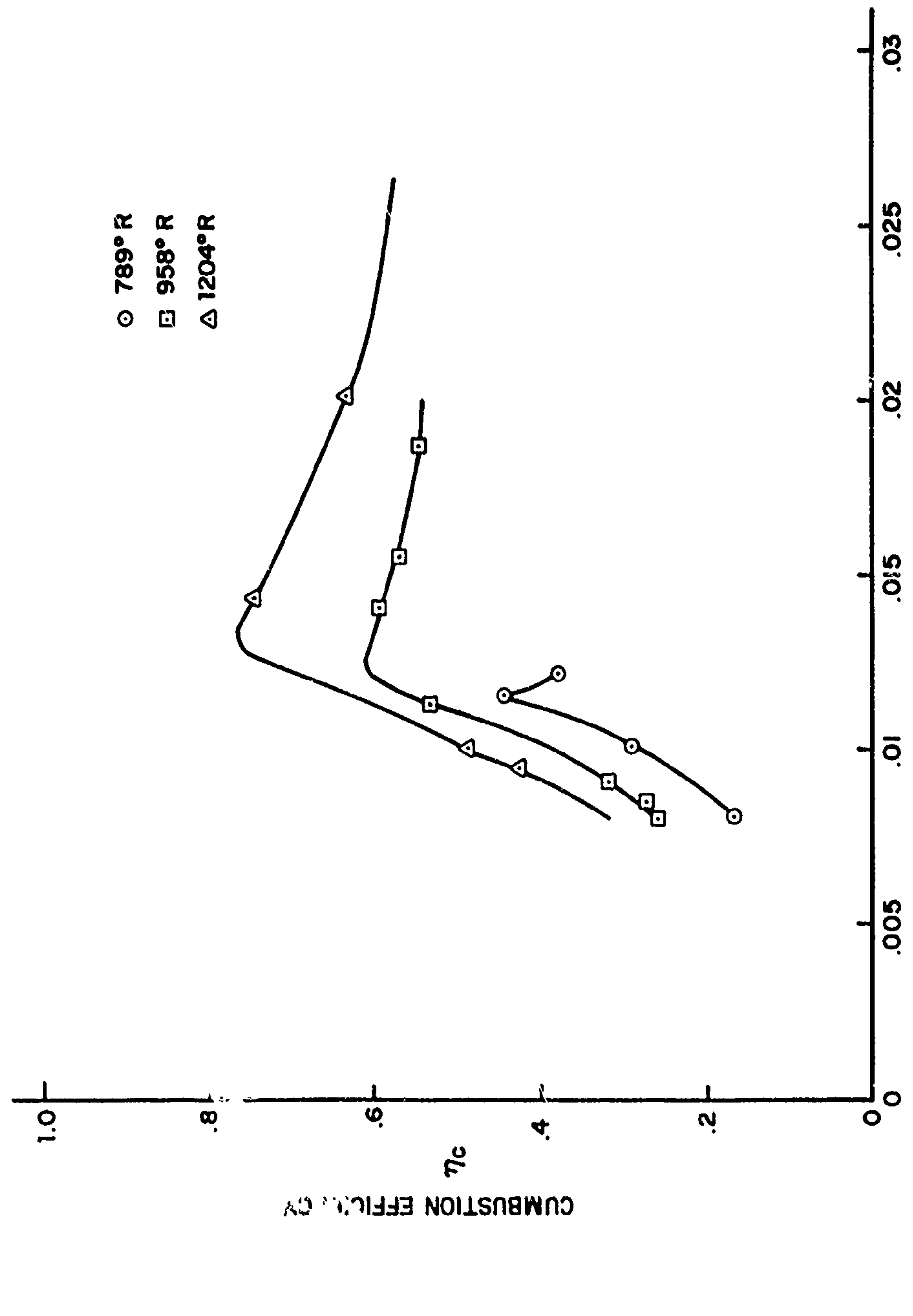


Figure 17. JP-4 Combustor Performance, 38% Nozzle, A_5/A_3

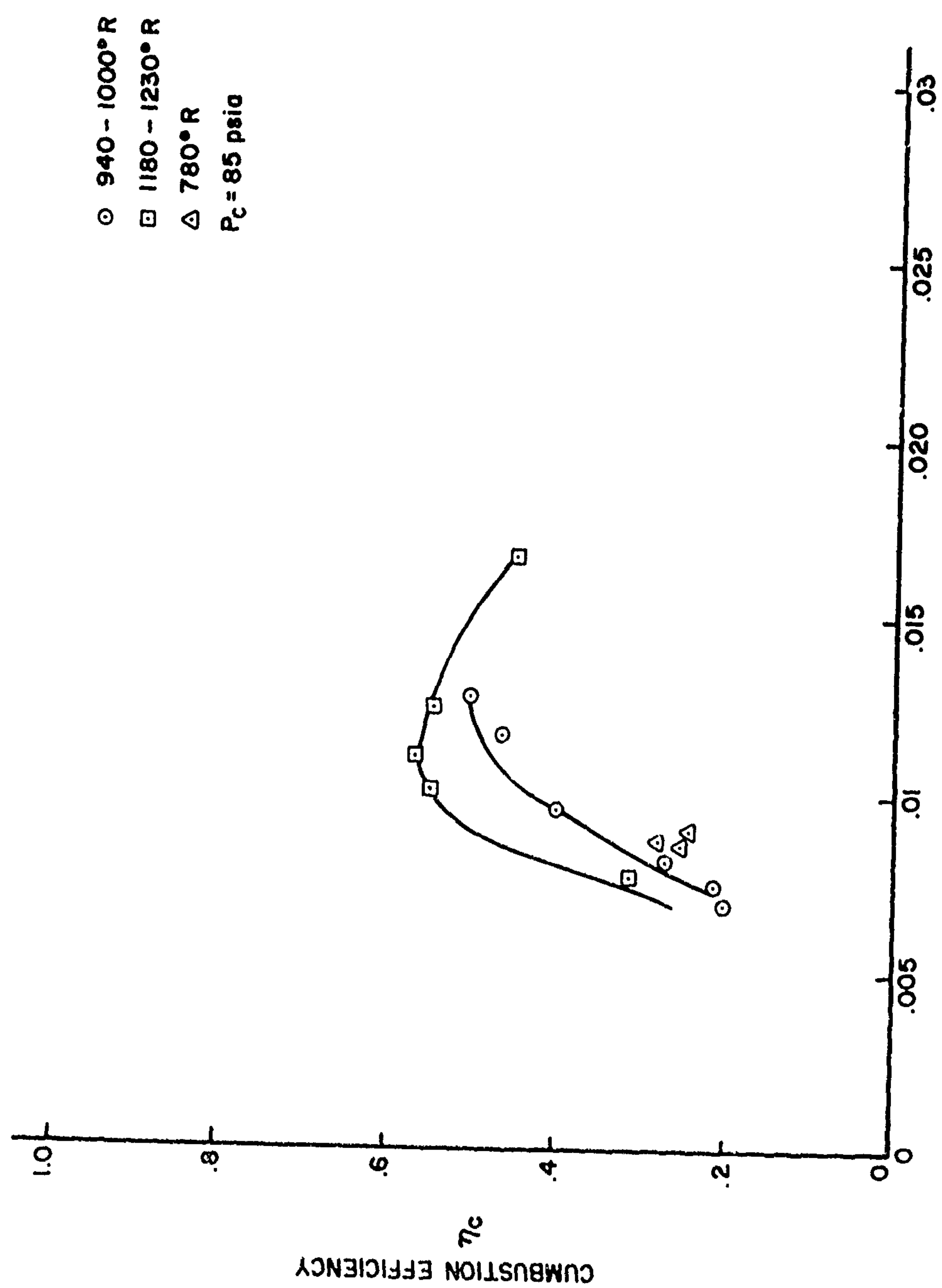


Figure 18. RJ-5 Combustor Performance, 38% Nozzle

SECTION VI

CONCLUSIONS

The penetration and spreading of liquid jets injected cross-stream using JP-4, RJ-5, water, glycol, and trichlorethylene have been correlated by the empirical Equations 6 and 7. The relationships agree with the work of Geery and Margetts (Reference 4).

Penetration was not affected by the viscosity of the liquids used in this experiment, even though the viscosity ratio (μ_j/μ_a) was changed by two orders of magnitude. When the viscosity ratio was plotted against the penetration expression, a line of near zero slope resulted, indicating the exponent on the ratio is near zero. This information extends the work of the previous investigation, since that and most of the other investigations in the past used only water as the injected liquid.

Finally, the penetration and spreading data was used to predict performance in a ramjet combustor connected to a coaxial inlet. No attempt was made to maximize efficiency, as all the work was done with a single, simple, tube injector. Good combustion resulted when Equation 8 was used to determine the position for the injector in the inlet for an overall fuel/air ratio of 0.01.

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APPENDIX I

DERIVATION OF LOCAL FUEL/AIR RATIO CURVES

$$(f/a)_\infty = \frac{\dot{m}_f}{\dot{m}_a} \tag{1}$$

$$\dot{m}_f = (f/a)_\infty \dot{m}_a = (f/a)_\infty \rho_a V_a A_a \tag{2}$$

$$(f/a)_L = \frac{\rho_f}{\rho_a} \qquad \text{where} \qquad \rho_f = \frac{\dot{m}_f}{V_f A_f} \tag{3}$$

But $A_f = X \cdot Y$ (the penetration and spreading distances)

$$(f/a)_L = \frac{\dot{m}_f}{\rho_a V_f X \cdot Y} \tag{4}$$

Now assuming $V_f \sim V_a$

$$(f/a)_L = \frac{\dot{m}_f}{\rho_a V_a X \cdot Y} \tag{5}$$

Substituting from Equation 2 into Equation 5

$$(f/a)_L = (f/a)_\infty \frac{A_a}{X \cdot Y} \tag{6}$$

From this work $X \cdot Y = (14.6 d_o^2)\left(\frac{V_j^2 \rho_j}{V_a^2 \rho_a}\right)^{.5}\left(\frac{Z}{d_o}\right)^{.6}$

$$\therefore \quad (f/a)_L = (f/a)_\infty \frac{A_a}{14.6 d_o^2}\left(\frac{V_a^2 \rho_a}{V_j^2 \rho_j}\right)^{.5}\left(\frac{Z}{d_o}\right)^{-.6} \tag{7}$$

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TABLE I

TEST CONDITIONS FOR PENETRATION

Type Liquid	Injector Diameter d_o (inch)	Liquid Velocity V_j (ft/sec)	Air Velocity V_a (ft/sec)	Liquid Density ρ_j (lb/ft3)	Air Density ρ_a (lb/ft3)	Air Viscosity μ_a (lb_m/ft-sec)	Liquid Viscosity μ_j (lb_m/ft-sec)	Penetration Length at Z=1 inch X (inch)
JP-4	0.0405	44	326	47.4	0.074	1.2×10^{-5}	64.39×10^{-5}	0.7271
		64		Same For All Test Conditions	Same For All Test Conditions	Same For All Test Conditions	Same For All Test Conditions	0.980
		76.2						1.075
		98						1.58
		116						1.83
		140						2.15
		170						2.34
JP-4	0.0405	44	464					0.600
		64						0.727
		197						1.96
		221						2.21
JP-4	0.0405	44	590					0.474
		64						0.696
		76.2						0.758
		98.0						0.950
		116						1.07
		140						1.20
		170						1.31
		197						1.58
		221						1.77
		257						1.96
JP-4	0.0405	44	710					0.453
		64						0.583
		98						0.777
		140						1.04
		197						1.36
		241						1.62
		257						1.71

TABLE I (Cont'd)

TEST CONDITIONS FOR PENETRATION

Type Liquid	Injector Diameter d_o (inch)	Liquid Velocity V_j (ft/sec)	Air Velocity V_a (ft/sec)	Liquid Density ρ_j (lb/ft3)	Air Density ρ_a (lb/ft3)	Air Viscosity μ_a (lbm/ft-sec)	Liquid Viscosity μ_j (lbm/ft-sec)	Penetration Length at Z=1 inch X (inch)
JP-4	0.0230	44	326	47.4	0.074	1.2×10^{-5}	64.4×10^{-5}	0.550
Same For All Test Conditions	Same For All Test Conditions	64		Same For All Test Conditions	Same For All Test Conditions	Same For All Test Conditions	Same For All Test Conditions	0.711
		76.2						0.776
		98						0.906
		116						1.16
		140						1.33
		170						1.49
		197						1.65
		221						1.81
		241						1.88
		257						1.97
		44	464					0.453
		64						0.550
		76.2						0.550
		98						0.679
		116						0.809
		140						0.939
		170						1.10
		197						1.19
		221						1.33
		241						1.42
		257						1.48
		64	590					0.405
		98						0.550
		140						0.744
		197						0.971
		241						1.13
		257						1.23

TABLE I (Cont'd)

TEST CONDITIONS FOR PENETRATION

Type Liquid	Injector Diameter d_c (inch)	Liquid Velocity V_j (ft/sec)	Air Velocity V_a (ft/sec)	Liquid Density ρ_j (lb/ft3)	Air Density ρ_a (lb/ft3)	Air Viscosity μ_a (lb_m/ft-sec)	Liquid Viscosity μ_j (lb_m/ft-sec)	Penetration Length at Z=1 inch X (inch)
JP-4	0.023	64	710	47.4	.074	1.2×10^{-5}	64.4×10^{-5}	0.356
		98						0.518
		140						0.615
		197						0.809
		241						0.971
		257						1.04
H_2O	0.0405	86	326	62.4	Same For All Test Conditions	Same For All Test Conditions	67.4×10^{-5}	1.70
		122						2.18
		150						Penetrated Across Tube
		172	464					2.20
		86	590					1.05
		172						1.66
RJ-5	0.0405	83	326	67.4			27.7×10^{-3}	1.28
		117						1.86
		166	464					1.86
		83	590					0.735
		166						1.57
Glycol	0.0405	82	326	69.19			13.41×10^{-3}	1.54
		116						2.18
		164	464					2.21
		82	590					0.832
		168						1.79
Trichlor	0.0405	71	326	90.83			37.2×10^{-5}	1.54
		101						2.01
		143	464					1.95
		71	590					0.906
		143						1.58